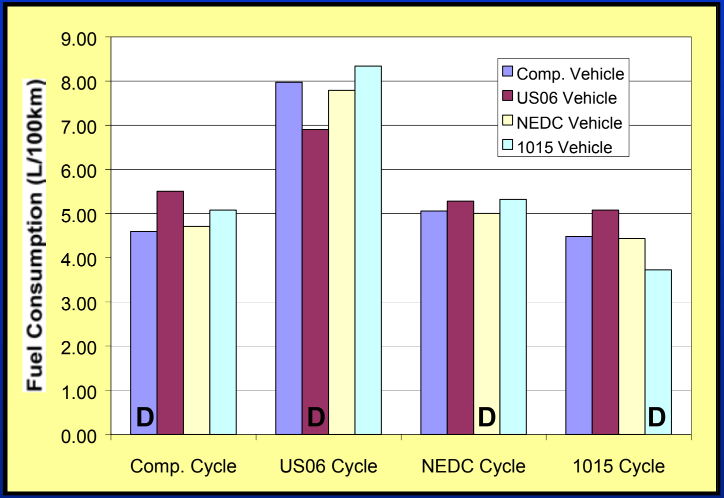
Vehicle System Impacts of Fuel Cell System Power Response Capability

Tony Markel
National Renewable Energy Laboratory

FutureCar Congress
June 3-6, 2002
Arlington, Virginia

Previous Work

- Impact of drive cycle on component sizes and energy management strategy (Wipke, et. al. EVS-18)
  - Optimizing for a specific drive cycle leads to significantly different vehicle designs
  - Designing for NEDC provides reasonably robust design



- Previous study assumption:
  - Assumed that the fuel cell system would be able to respond from 10 to 90% power in 2 seconds (DOE 2004 target)
  - *This study varies the response time/rate of the FC*

Technology Status

- FTT paper by Honeywell lists a current 0 to full power transient capability of 20 seconds
  - Mainly an issue of inlet stream conditioning
    - Flow
    - Temperature
    - Pressure
    - Humidity
- 2000 SAE Congress paper provides data showing a transient completed in less than one second
- Study by L. Potter (Johnson Matthey) for the ETSU
  - fuel cell transient response capability influential on the component sizing in a hybrid transit bus application

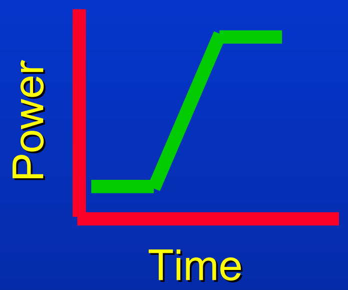
To be answered by this study:

- How will the optimized vehicle component sizes and control strategy vary with improvements in the transient response time?
  - Hybridized vehicle
  - Neat fuel cell vehicle

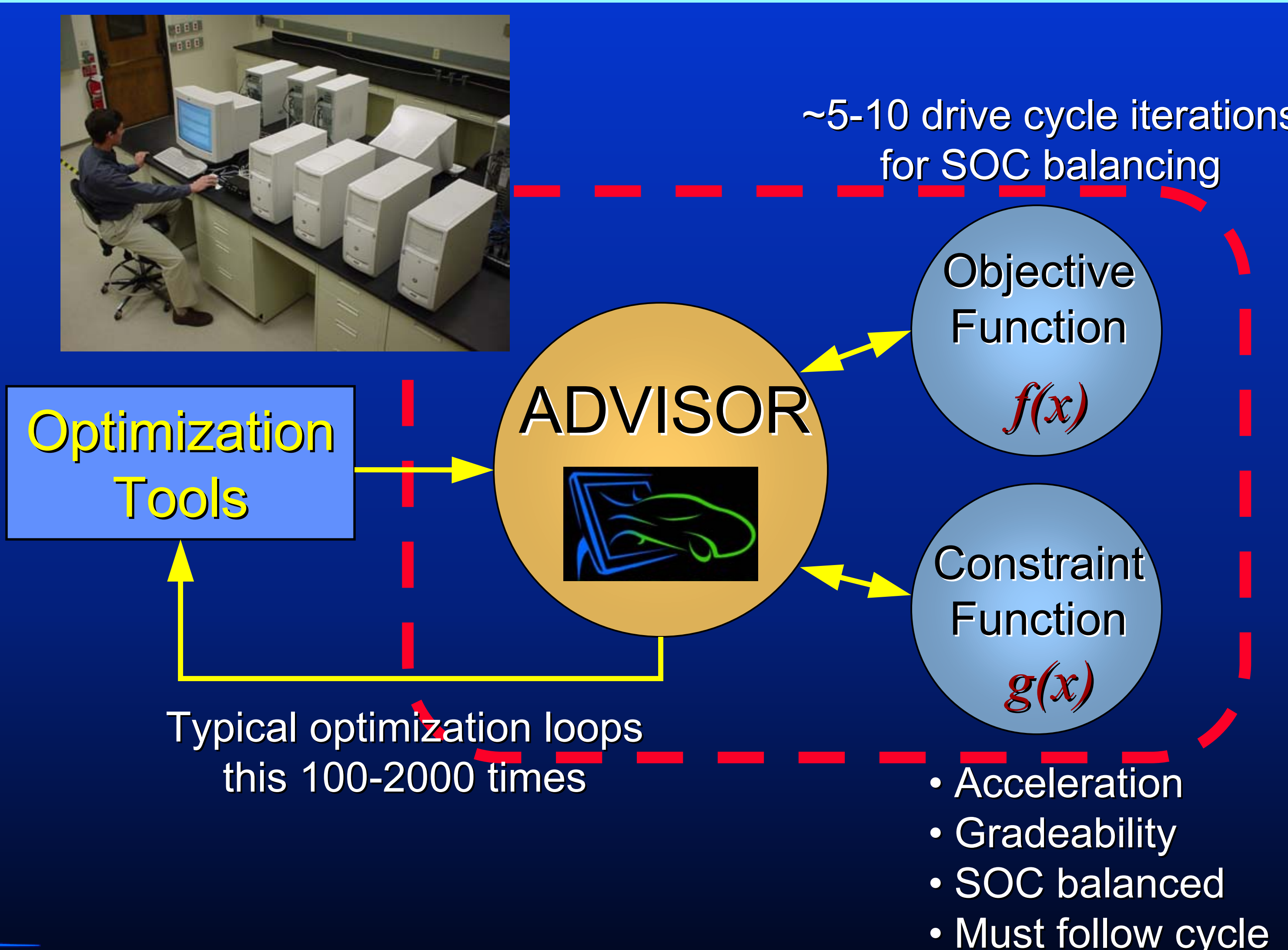
- Also, if the fast response time target is relaxed, how could this benefit FC vehicle design (size, cost, etc.)

What was done …

- Starting from previous (EVS-18) results,
  - Sweep transient response rate parameter
    - Set points: 0, 2, 5, 10, 20, 40s
    - Three drive cycles
      - City/Highway Composite (standard benchmark)
      - US06 (aggressive - expected to be more influential)
      - NEDC (provides robust designs)
    - Vehicles
      - Hybrid
      - Non-hybrid (0, 2, 5, and 7s only)
        - Greater than 7s provides unreasonable solutions



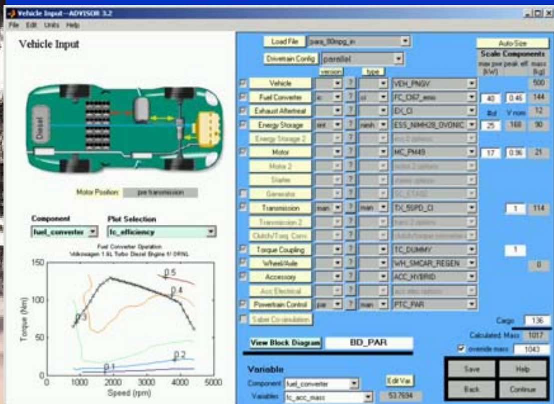
Using ADVISOR in an Optimization Loop as both the Function Call and Constraint Evaluation



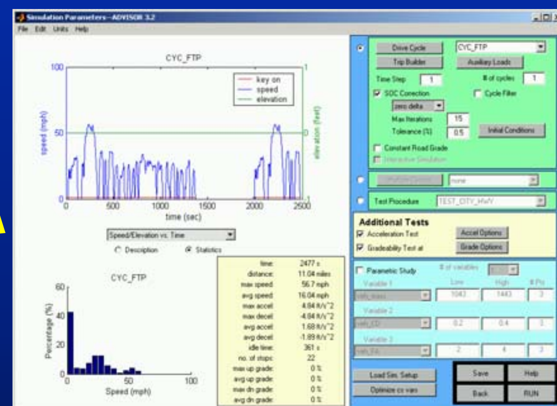
Three Main ADVISOR GUI Screens – 'GUI-Free' version Used for Optimization

ADVISOR 2002
Advanced Vehicle Simulator

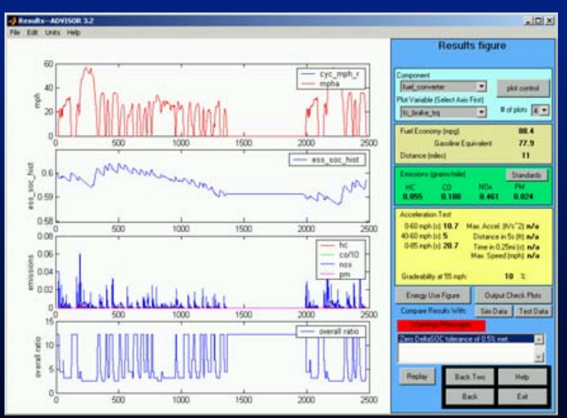
Vehicle Input



Simulation Setup



Results



Optimization Problem Definition

- Objective
  - Maximize fuel economy of fuel cell powered hybrid electric SUV
- Constraints
  - Performance equivalent to comparable conventional vehicle
    - 6 inequality constraints, such as accel., grade, SOC balanced…
- 8 Total Design Variables
  - 4 Component Characteristics
    - fuel cell peak power
    - traction motor peak power
    - number of battery modules
    - capacity of battery modules
  - 4 Control Strategy
    - low power fuel cell power cut-off
    - high power fuel cell power cut-off
    - minimum fuel cell off time
    - charge power set point

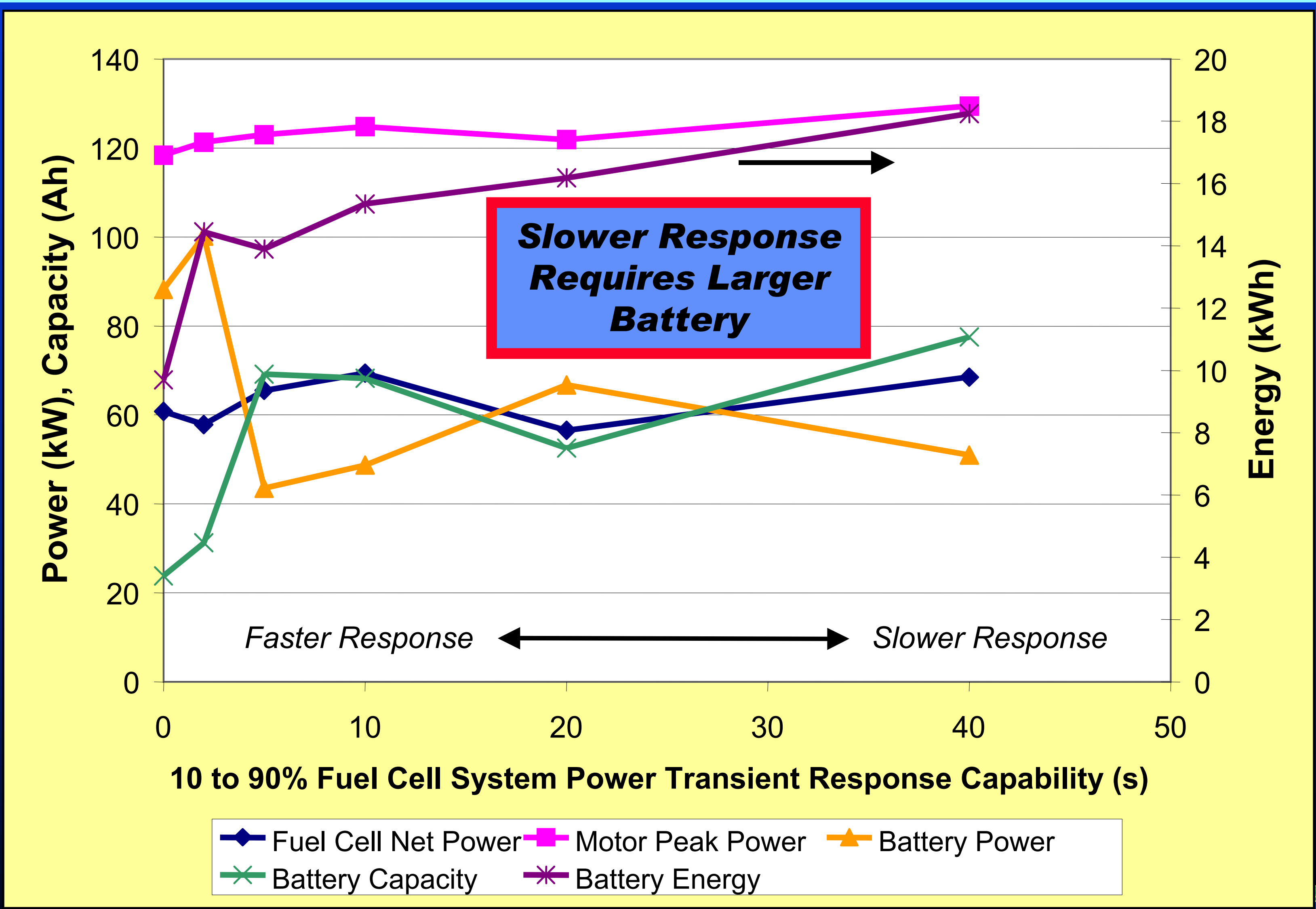
Vehicle Specifications

Vehicle Type	Rear wheel drive mid-size SUV (i.e. Jeep Grand Cherokee)
Baseline Conventional Vehicle Mass	1788 kg
HEV Glider Mass (No Powertrain)	1202 kg
Rolling Resistance	0.012
Wheel Radius	0.343 m
Frontal Area	2.66 m^2
Coefficient of Aerodynamic Drag	0.44

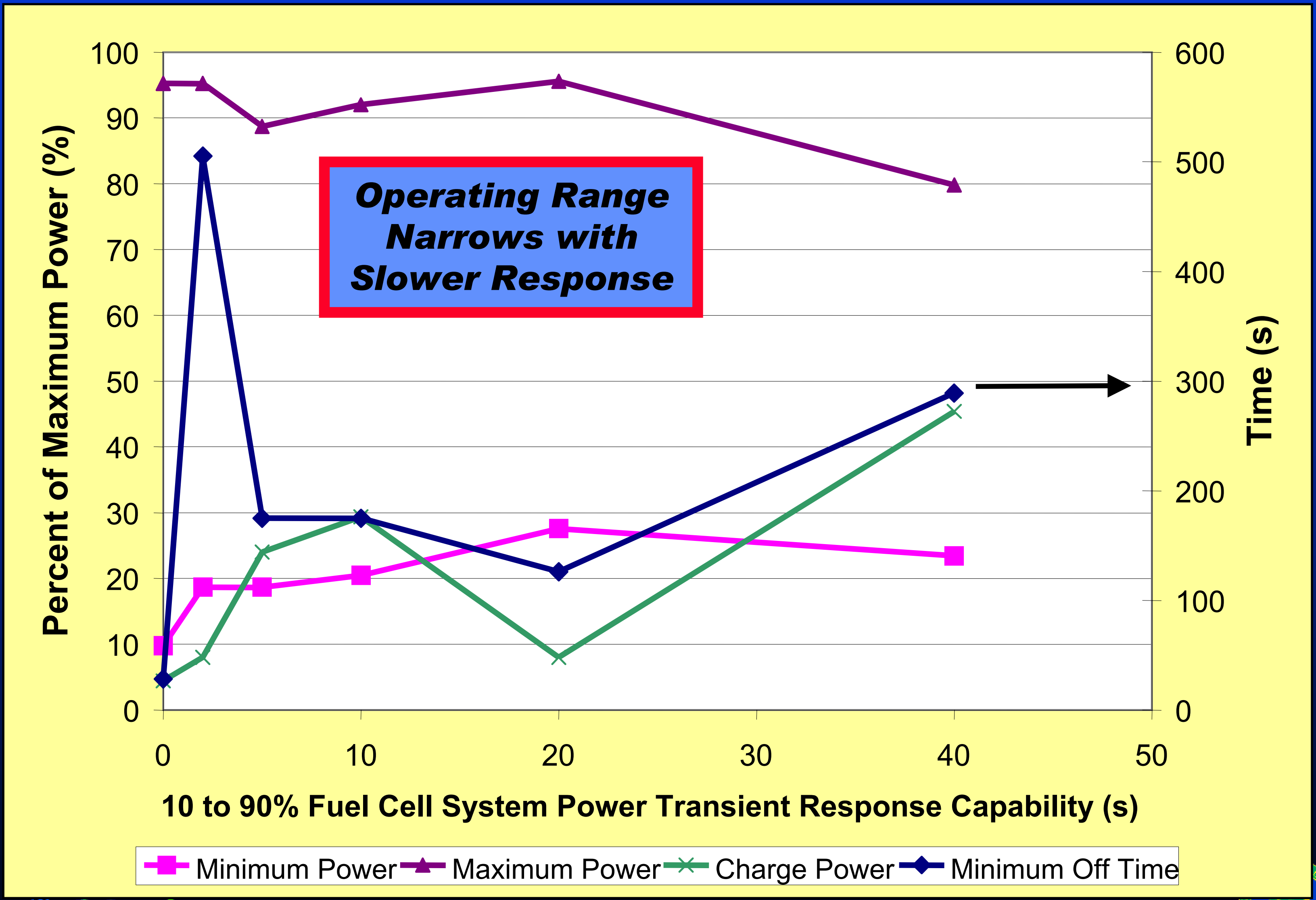
Baseline Components

Component	Description
Fuel Converter	Efficiency vs. net power performance data for 52 kW (net) Honeywell pressurized fuel cell system
Motor/Controller	AC induction motor developed by Virginia Power Technologies 83 kW @ 275 Vmin
Energy Storage System	Ovonic 45 Ah NiMH battery modules

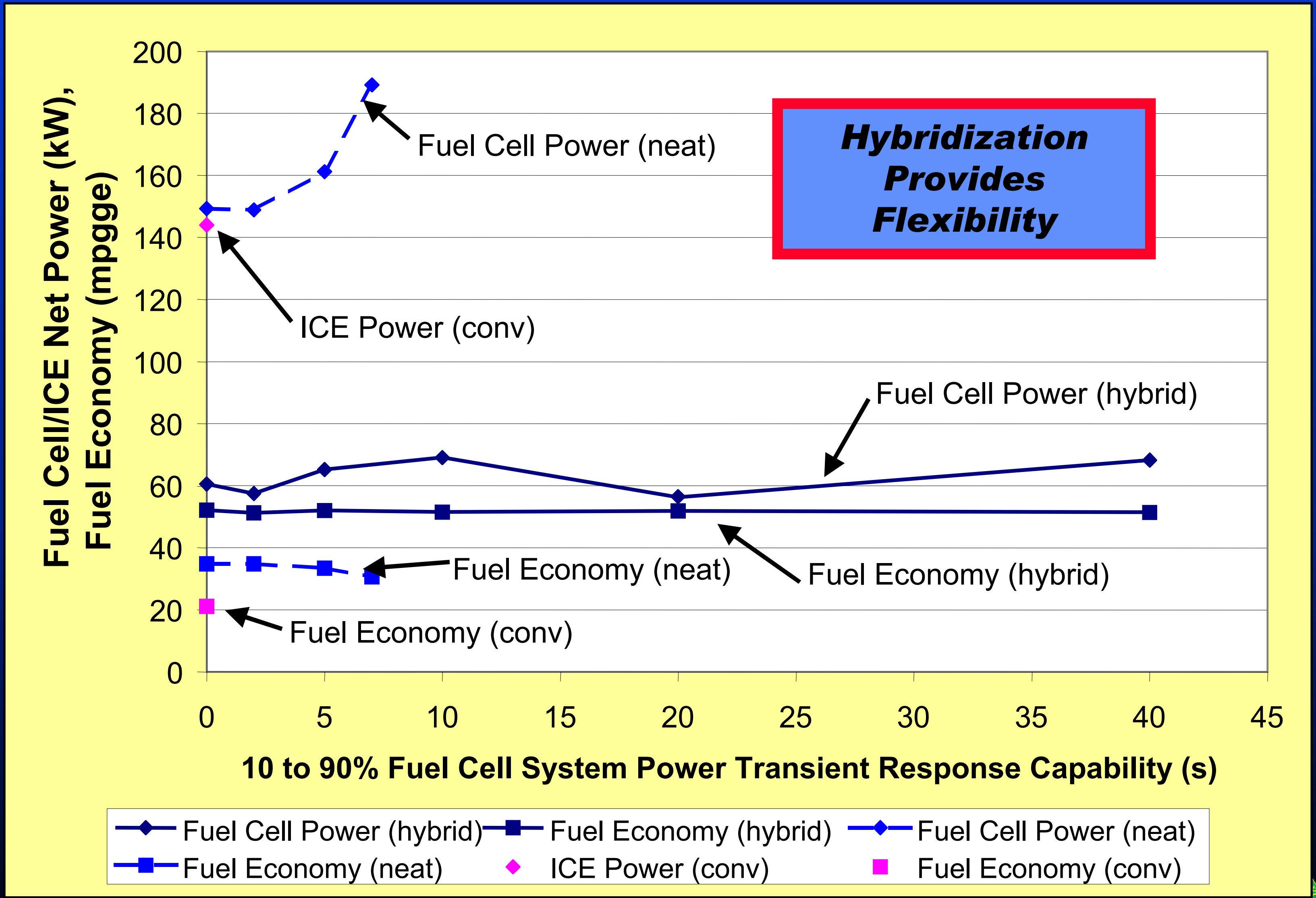
Variation of Component Sizes (absolute)



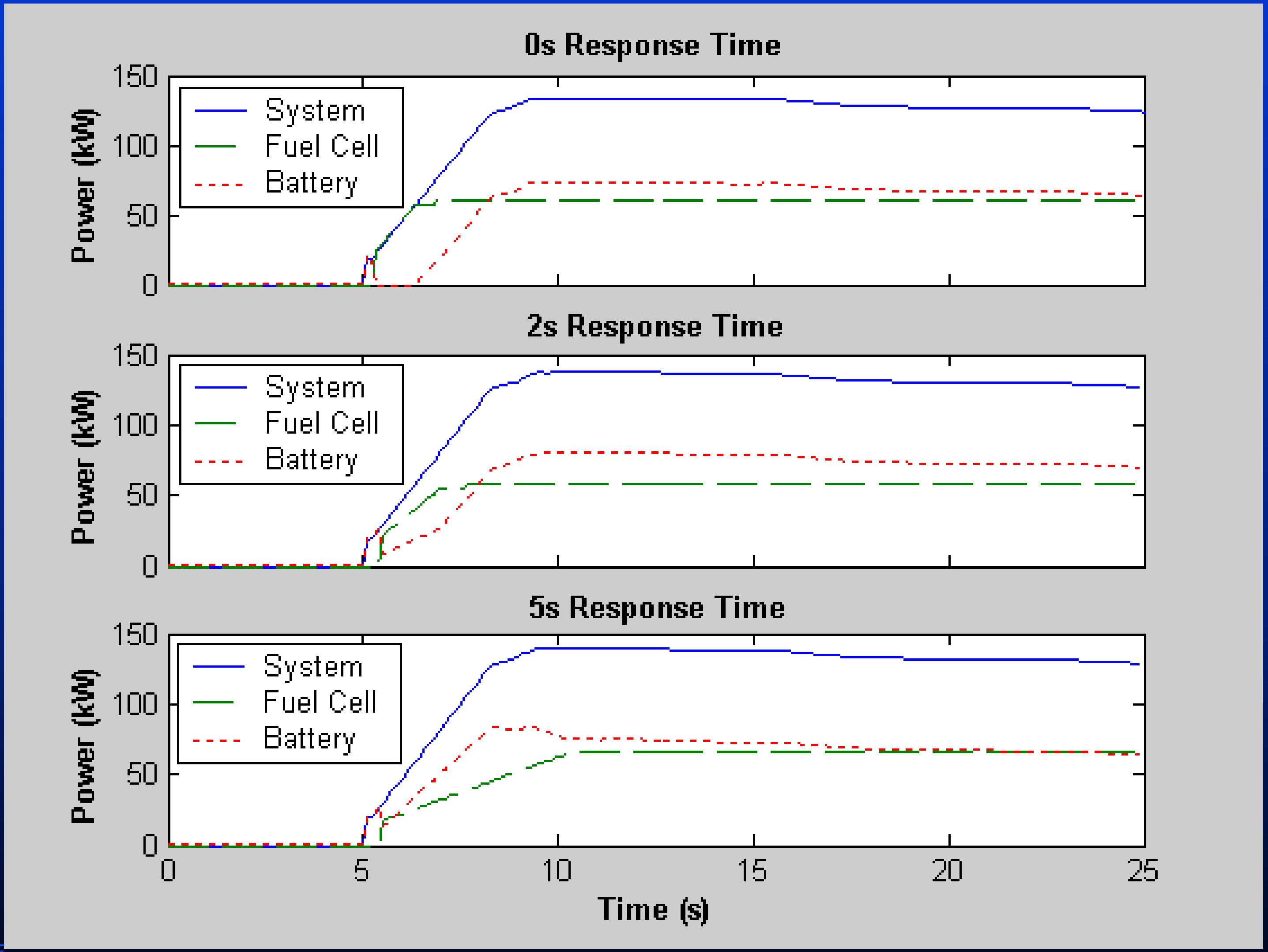
Variation of Control Strategy Parameters



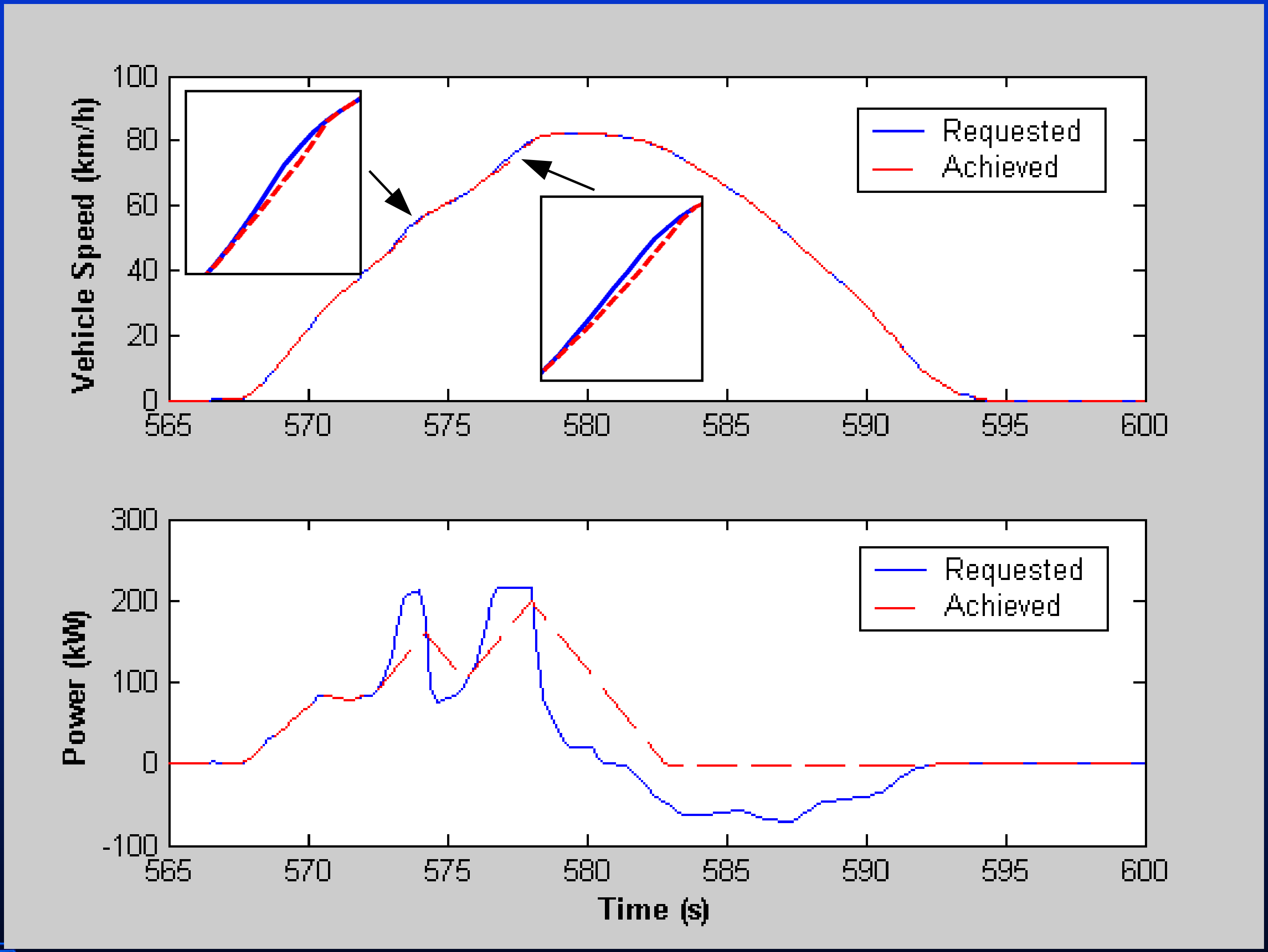
Comparison of Hybrid, Neat, and Conventional Vehicles



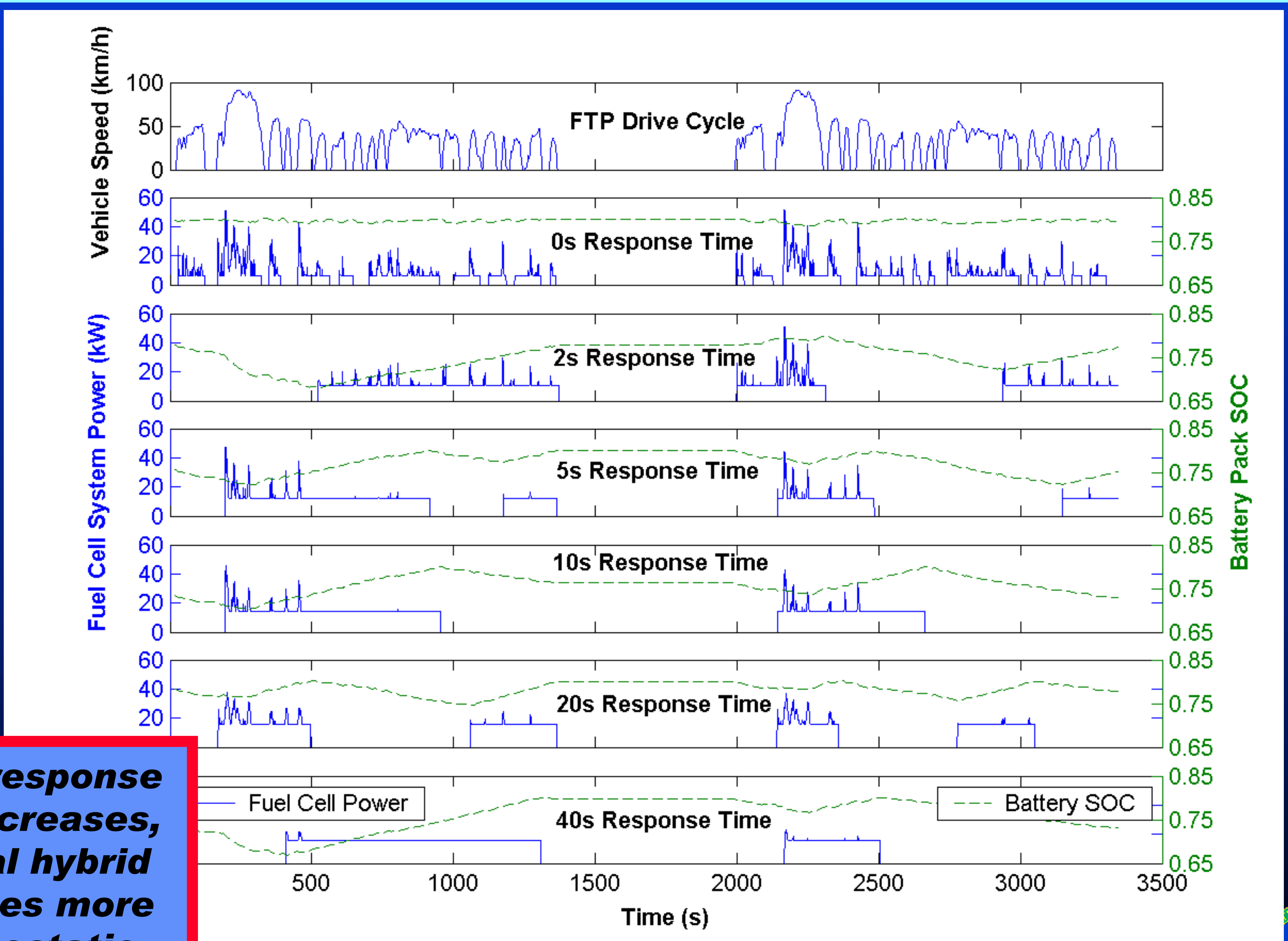
Distribution of Power During Acceleration Event for Hybrid Fuel Cell SUV



Fuel Cell System in FCEV with Slow Transient Response (5s) on US06 Cycle



Operating Characteristics of Hybrids Optimized For Combined City/Highway Driving



As FC response time increases, optimal hybrid becomes more thermostatic

Optimization of Fuel Cell Vehicle Design Provides Insight into System Trade-offs

Proceedings of IMECE:
International Mechanical Engineering Congress and Exposition
November 16, 2001 New York, New York

OPTIMIZATION TECHNIQUES FOR HYBRID ELECTRIC VEHICLE ANALYSIS USING ADVISOR

18th Electric Vehicle Symposium - Berlin, Germany - October 20-24, 2001

Optimizing Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV

Keith Wipke, Tony Markel, and Doug Nelson

2002 - FCC - 24

Vehicle System Impacts of Fuel Cell System Transient Response Capability

Tony Markel and Keith Wipke
National Renewable Energy Laboratory

Doug Nelson
Virginia Polytechnic University and State Institute

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ABSTRACT

The impacts of fuel cell system transient response capability on optimal hybrid and neat fuel cell vehicle configurations have been explored. Vehicle system optimization was performed with the goal of maximizing fuel economy over a drive cycle. Optimal hybrid vehicle designs were derived for fuel cell systems with 10 to 90% power transient response times of 0, 2, 5, 10, 20, and 40 seconds. Optimal neat fuel cell vehicles where generated for responses times of 0, 2, 5, and 7 seconds. DIRECT, a derivative-free optimization algorithm, was used in conjunction with ADVISOR, a vehicle systems analysis tool, to systematically change both powertrain component sizes and the vehicle energy management strategy parameters to provide optimal vehicle system configurations for the range of transient response times.

Results indicate that the transient response time of the fuel cell system significantly influences the preferred powertrain component characteristics and the resulting fuel economy in a neat fuel cell vehicle. Slower transient response capability leads to larger component sizes and lower fuel economy. For a hybrid fuel cell vehicle, optimal combinations of component sizes and energy management strategy parameters can be found that lead to only a minor variation in vehicle fuel economy with respect to fuel cell system transient response capability.

INTRODUCTION

ADVISOR is a vehicle simulator capable of simulating conventional, hybrid electric, electric, and fuel cell vehicles [1, 2]. It uses drivetrain component characteristics to estimate vehicle fuel economy and emissions over defined drive cycles as well as other quantitative performance metrics (i.e., maximum-effort acceleration, gradeability). Roughly 30 different drive cycles and numerous complex test procedures can be used to assess the vehicle fuel economy, emissions, and performance under various simulated test conditions.

Because of the complexity of hybrid electric vehicles (HEVs), including issues such as component sizing, energy management strategy, and battery state-of-charge (SOC) balancing, optimization becomes necessary to give results that can be accurately compared with other vehicles. ADVISOR executes quickly, allowing a single drive cycle (~1000 seconds) to be run on the order of 20 seconds on a standard PC. It is well suited to being linked to optimization routines which may need to evaluate several thousand designs to determine the best.

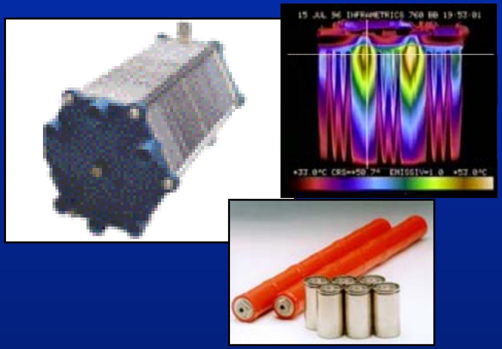
ADVISOR v3.1 was used in this study as the 'objective function' call within the MATLAB environment. Various optimization algorithms have been linked to ADVISOR to both understand the differences in their approach and their effectiveness in satisfying the needs of finding optimal solutions in the challenging design space of hybrid electric vehicles [3]. It was concluded that the non-gradient based methods of the DIRECT algorithm were extremely effective in finding the regions likely to contain local and possibly global optimum solutions, but required considerable amount of solution time to converge onto the answer within a small tolerance.

Previous work relating to optimization of hybrid vehicles has included efforts at University of California, Davis [4] that examined whether, and under which conditions, hybridization of a fuel cell vehicle would be beneficial. More recently, collaborative work was performed with Virginia Polytechnic Institute and State University (Virginia Tech) on sizing of components for fuel cell hybrids, which this work will build upon [5]. Atwood, et. al. concluded that some level of fuel cell system hybridization was beneficial to the design. Based on a revision to their published results, it was shown that the best City/Highway fuel economy could be obtained at a fuel cell to total power (fuel cell + battery) ratio of 0.26. This translated to a fuel cell providing a net peak power of 52 kW and a 150 kW battery pack for a GMC Suburban vehicle (a total of 202 kW was required to meet the performance requirements). An assumption of this study was that the vehicle mass will remain constant

- Determined that derivative-free optimization algorithms necessary for complex design space of HEVs
- Drive cycle influences optimal degree of hybridization and control parameters
  - NEDC provides robust design
- Fuel cell transient response capability critical for neat fuel cell vehicle
- An optimized hybrid design can nullify the effects of fuel cell transient response

Areas for Further Exploration

- Fuel cell system start-up, shut-down, and idling
- Energy storage technology selection for fuel cell vehicles
- Include multiple objectives
  - cost, volume, durability, …



- Vehicle system optimization with respect to other fuel cell system design attributes
  - specific cost, specific power, power density, …

Summary and Conclusions

- The fuel cell system characteristics affect both the optimal control and component sizing with respect to fuel economy

- Optimal hybrid vehicle scenarios can be derived that take advantage of, or compensate for, fuel cell system operating characteristics (such as response time)

- Fast transient response capability will be critical for neat fuel cell vehicles